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Application of SEDEA to evaluation of degree of harmony between water resources and economic development

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Abstract: This paper introduces the method of data envelopment analysis (DEA) for evaluation of the degree of harmony between water resources and economic development of the water conservancy area of China's South-to-North Water Diversion Project (SNWDP). For this evaluation, a super-efficiency DEA (SEDEA) model was developed based on the super-efficiency method. To verify the applicability of the SEDEA model, both the SEDEA model and a normal-efficiency DEA (NEDEA) model were used to evaluate the degree of harmony between water resources and economic development of typical cities in the SNWDP water conservancy area. The results show that the SEDEA model ranks the degree of harmony of typical cities more efficiently than the NEDEA model, and thus can better evaluate the degree of harmony between water resources and economic development of different cities than the NEDEA model. Furthermore, the SEDEA model can be applied as an operational research tool in regional water resources management.

Key words: *degree of harmony; super-efficiency DEA model; water conservancy area; South-to-North Water Diversion Project*

1 Introduction

Evaluation of the degree of harmony between water resources and economic development is currently a hot topic in water science research (WRFSSGCAS 2009). Zhang et al. (1999) proposed that water resources be developed in coordination with the national economy, and constructed a system dynamics model for coordinative development between water resources and the national economy of China. Zuo (2007) developed an embedded system dynamics model for a human water system. Wang and Ma (2006) utilized a holistic coupling model to simulate the coordinative development between water resources and the national economy of China, finding that this model had a higher precision in complex system analysis than previous models. These studies took place mainly on the scale of China as a whole, on the scale of

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basins such as the Talimu River Basin, and on a regional scale such as Zhengzhou City. Although there is some literature on the degree of harmony between water resources and economic development of the water conservancy area of China's South-to-North Water Diversion Project (SNWDP) (Zhou and Shi 2007; Feng et al. 2008; Sun et al. 2009; Ma 2009), and on the application of DEA (data envelopment analysis) in water resources management (Wang 2007; Liu and Li 2008; Sun and Yan 2008; Xie and Yuan 2008; Sun and Liu 2009; Ma et al. 2009; Wang 2010; Chen 2010; Yu et al. 2010), to the best of our knowledge there is no literature on ranking of cities in the SNWDP water conservancy area.

In this study, to evaluate and rank the degree of harmony between water resources and economic development in the SNWDP water conservancy area, an SEDEA (super-efficiency DEA) model was developed based on the super-efficiency method. To verify the applicability of the SEDEA model, a normal-efficiency DEA (NEDEA) model was also evaluated using the same data.

2 Evaluation index system

2.1 Definition of degree of harmony between water resources and economic development

Water resources are an important strategic resource for China's national economy. There should be efficient coordination between water resources and economic development in China, in areas such as economic growth, life stability, environmental friendliness, and full employment; that is to say, there should be harmony between water resources and economic development. Therefore, the degree of harmony between water resources and economic development is, in fact, the degree of efficiency in the coordination between water resources and economic development, meaning the degree of integration and synchronization of water resources, economic growth, life stability, environmental friendliness, and full employment. It represents the extent to which water resources meet economic development needs, and is the value of an objective function composed of water resources inputs including water supply, water employees, and water investment, and economic development outputs including GDP per capita, water consumption per capita, the urban domestic sewage treatment rate, and the employment rate of typical cities within China's SNWDP water conservancy area.

2.2 Evaluation index system of degree of harmony between water resources and economic development

According to the definition of the degree of harmony between water resources and economic development given above, the combined principles of scientific, rational, objective, and advisable characteristics, related literature, and the comprehensive evaluation index system framework of water resources and economic development established by an expert counseling method (Ma 2009), we characterized typical cities within China's SNWDP water conservancy area depending on data availability. The evaluation index system of the degree of harmony between water resources and economic development is composed of a target layer, a criterion layer, and an index layer (as shown in Table 1). The target layer is the degree of harmony. The criterion layer comprises water resources inputs and economic development outputs. The index layer comprises the water supply (x_1), a resources input; employees of water supply departments (x_2), a labor input; water investment (x_3), a capital input; GDP per capita (y_1), an economic output; water consumption per capita (y_2), which represents quality of life; the urban domestic sewage treatment rate (y_3), which represents the quality of the environment; and the employment rate (y_4), which represents social stability.

Table 1 Evaluation index system of degree of harmony between water resources and economic development

Target layer	Criterion layer	Index layer
Degree of harmony	Water resources inputs	x_1
		x_2
		x_3
	Economic development outputs	y_1
		y_2
		y_3
		y_4

3 DEA models

3.1 NEDEA model

To evaluate the performance of different sections or regions based on input variables such as investment and labor and output variables such as production and benefits, appropriate weighting should be adopted. Charnes et al. (1978) provided the original DEA-CRS (constant returns to scale) model, later extended to a VRS (variable returns to scale) model by Banker et al. (1984). These NEDEA models are known by the acronyms CCR (from the authors' names, Charnes, Cooper, and Rhodes) and BCC (from the authors' names, Banker, Charnes, and Cooper), respectively. In NEDEA models, a decision-making unit (DMU) is considered to be efficient if its performance relative to other DMUs cannot be improved. In the absence of price data or preferential weightings of inputs and outputs, all efficient DMUs have equal scores of 100%, and rank equally in terms of performance. Inefficient DMUs have scores of less than 100% with an output orientation, and greater than 100% with an input orientation (Wei 2004). Suppose the jth DMU has input $\boldsymbol{X}_j$ and output $\boldsymbol{Y}_j$, where $\boldsymbol{X}_j = \left(x_{1j}, x_{2j}, \cdots, x_{ij}, \cdots, x_{mj}\right)^{\mathrm{T}}$, $\boldsymbol{Y}_j = \left(y_{1j}, y_{2j}, \cdots, y_{rj}, \cdots, y_{sj}\right)^{\mathrm{T}}$, $x_{ij} > 0$, $y_{rj} > 0$, $i = 1,2,\cdots,m$, and $r = 1,2,\cdots,s$. The weight vector of output $\boldsymbol{Y}_j$ is $\boldsymbol{u} = \left(u_1, u_2, \cdots, u_r, \cdots, u_s\right)^{\mathrm{T}} \geq 0$, and the weight vector of input $\boldsymbol{X}_j$ is $\boldsymbol{v} = \left(v_1, v_2, \cdots, v_i, \cdots, v_m\right)^{\mathrm{T}} \geq 0$. Then, the efficiency index h_j is

$$h_j = \frac{\boldsymbol{u}^{\mathrm{T}}\boldsymbol{Y}_j}{\boldsymbol{v}^{\mathrm{T}}\boldsymbol{X}_j} \qquad j = 1, 2, \cdots, n \tag{1}$$

Based on Eq. (1), to evaluate the efficiency of the j_0th DMU, for the sake of convenience, with $\boldsymbol{X}_0 = \boldsymbol{X}_{j_0}$, $\boldsymbol{Y}_0 = \boldsymbol{Y}_{j_0}$, and $1 \le j_0 \le n$, we can easily construct the primal programming as follows:

$$\begin{aligned} &\max \frac{\boldsymbol{u}^{\mathrm{T}}\boldsymbol{Y}_0}{\boldsymbol{v}^{\mathrm{T}}\boldsymbol{X}_0} \\ &\text{s.t.} \ \frac{\boldsymbol{u}^{\mathrm{T}}\boldsymbol{Y}_j}{\boldsymbol{v}^{\mathrm{T}}\boldsymbol{X}_j} \le 1 \quad j = 1, 2, \cdots, n \\ &\qquad \boldsymbol{u} \ge 0, \quad \boldsymbol{v} \ge 0 \end{aligned} \tag{2}$$

Then, with Charnes-Cooper transformation $\boldsymbol{\omega} = \frac{\boldsymbol{v}}{\boldsymbol{v}^{\mathrm{T}}\boldsymbol{X}_0}$, and $\boldsymbol{\mu} = \frac{\boldsymbol{u}}{\boldsymbol{v}^{\mathrm{T}}\boldsymbol{X}_0}$, the fractional programming can be converted to linear programming:

$$\begin{aligned} &\max \boldsymbol{\mu}^{\mathrm{T}}\boldsymbol{Y}_0 \\ &\text{s.t.} \ \boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{X}_j - \boldsymbol{\mu}^{\mathrm{T}}\boldsymbol{Y}_j \ge 0 \quad j = 1, 2, \cdots, n \\ &\qquad \boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{X}_0 = 1 \\ &\qquad \boldsymbol{\omega} \ge 0, \ \boldsymbol{\mu} \ge 0 \end{aligned} \tag{3}$$

The dual programming for the CCR model is as follows (Charnes et al. 1978):

$$\begin{aligned} &\min \theta \\ &\text{s.t.} \ \sum_{j=1}^{n} \boldsymbol{X}_j \lambda_j \le \theta \boldsymbol{X}_0 \\ &\qquad \sum_{j=1}^{n} \boldsymbol{Y}_j \lambda_j \ge \boldsymbol{Y}_0 \\ &\qquad \lambda_j \ge 0 \end{aligned} \tag{4}$$

where λ_j represents the optimal solution to Eq. (4), and θ is an objective function value (here it also means the degree of harmony).

With the m-dimensional vector $\boldsymbol{S}^- = \left(s_1^-, s_2^-, \cdots, s_i^-, \cdots, s_m^-\right)^{\mathrm{T}}$, where the surplus variable $s_i^- \ge 0$, and $i = 1, 2, \cdots, m$, and the s-dimensional vector $\boldsymbol{S}^+ = \left(s_1^+, s_2^+, \cdots, s_r^+, \cdots, s_s^+\right)^{\mathrm{T}}$, where the slack variable $s_r^+ \ge 0$, and $r = 1, 2, \cdots, s$, we obtain the NEDEA model, as follows:

$$\begin{aligned} &\min \theta \\ &\text{s.t.} \ \sum_{j=1}^{n} \boldsymbol{X}_j \lambda_j + \boldsymbol{S}^- = \theta \boldsymbol{X}_0 \\ &\qquad \sum_{j=1}^{n} \boldsymbol{Y}_j \lambda_j - \boldsymbol{S}^+ = \boldsymbol{Y}_0 \\ &\qquad \lambda_j \ge 0 \\ &\qquad \boldsymbol{S}^- \ge 0, \quad \boldsymbol{S}^+ \ge 0 \end{aligned} \tag{5}$$

Given the time factor t, time lag k between $\boldsymbol{X}_j$ and $\boldsymbol{Y}_j$, and a non-Archimedean infinitesimal ε, defining $\boldsymbol{X}_j=\boldsymbol{X}_j(t)$, and $\boldsymbol{Y}_j=\boldsymbol{Y}_j(t+k)$, we obtain the improved NEDEA model, as follows:

$$\min\left[\theta-\varepsilon\left(\hat{\boldsymbol{e}}^{\mathrm{T}}\boldsymbol{S}^{-}+\boldsymbol{e}^{\mathrm{T}}\boldsymbol{S}^{+}\right)\right] \tag{6}$$

$$\begin{aligned}
\text{s.t.}\quad & \sum_{j=1}^{n}\boldsymbol{X}_j(t)\lambda_j+\boldsymbol{S}^{-}=\theta\boldsymbol{X}_0(t)\\
& \sum_{j=1}^{n}\boldsymbol{Y}_j(t+k)\lambda_j-\boldsymbol{S}^{+}=\boldsymbol{Y}_0(t+k)\\
& \lambda_j\geq 0\\
& \boldsymbol{S}^{-}\geq 0,\ \boldsymbol{S}^{+}\geq 0\\
& t\geq 0,\ k\geq 0
\end{aligned}$$

where $\boldsymbol{e}=(1,\cdots,1)^{\mathrm{T}}\in\boldsymbol{R}^{s}$, $\hat{\boldsymbol{e}}=(1,\cdots,1)^{\mathrm{T}}\in\boldsymbol{R}^{m}$, $\boldsymbol{X}_j(t)=\left(x_{1j}(t_1),x_{2j}(t_2),\cdots,x_{mj}(t_m)\right)^{\mathrm{T}}$, and $\boldsymbol{Y}_j(t+k)=\left(y_{1j}(t_1+k_1),y_{2j}(t_2+k_2),\cdots,y_{sj}(t_s+k_s)\right)^{\mathrm{T}}$.

3.2 SEDEA model

Banker and Gifford (1988) suggested the use of SEDEA to screen out observations with gross data errors, and obtained more reliable efficiency estimates after removing the identified outliers. Andersen and Petersen (1993) improved the SEDEA model, in which the super-efficiency scores can be obtained using the standard CCR and BCC models. Dula and Hickman (1997), Seiford (1997), and Seiford and Zhu (1999) have proved theorems providing necessary and sufficient conditions for infeasibility of the conventional super-efficiency model. The advantage of the conventional SEDEA model is that it permits ranking of efficient DMUs. The disadvantage is that the conventional SEDEA model does not consider time lag between inputs and outputs.

Based on the improved NEDEA model (Eq. (6)) and the aforementioned literature, if $j\neq j_0$, then our improved SEDEA model is

$$\min\left[\theta-\varepsilon\left(\hat{\boldsymbol{e}}^{\mathrm{T}}\boldsymbol{S}^{-}+\boldsymbol{e}^{\mathrm{T}}\boldsymbol{S}^{+}\right)\right] \tag{7}$$

$$\begin{aligned}
\text{s.t.}\quad & \sum_{\substack{j=1\\ j\neq j_0}}^{n}\boldsymbol{X}_j(t)\lambda_j+\boldsymbol{S}^{-}=\theta\boldsymbol{X}_0(t)\\
& \sum_{\substack{j=1\\ j\neq j_0}}^{n}\boldsymbol{Y}_j(t+k)\lambda_j-\boldsymbol{S}^{+}=\boldsymbol{Y}_0(t+k)\\
& \lambda_j\geq 0\\
& \boldsymbol{S}^{-}\geq 0,\ \boldsymbol{S}^{+}\geq 0\\
& t\geq 0,\ k\geq 0
\end{aligned}$$

The advantage of our SEDEA model (Eq. (7)) is that it not only permits ranking of efficient DMUs, but also considers time lags between inputs and outputs.

4 Application

To verify the applicability of the SEDEA model, both the NEDEA and SEDEA models were applied to the SNWDP water conservancy area to evaluate the degree of harmony between water resources and economic development of typical cities in China.

4.1 Study area

The near-term target of the SNWDP general program is to supply water to cities in the water conservancy area, including Tianjin and Jinan along the eastern route, and Beijing and Shijiazhuang along the central route. The 16 cities listed in Table 2 were selected as typical cities due to their importance and representativeness in terms of size and geographical location.

Table 2 Typical cities selected in SNWDP water conservancy area

Route	Basin	Province	City	DMU
Eastern route	Huaihe Basin	Jiangsu	Yangzhou	YZ
			Huai'an	HA
			Xuzhou	XZ
	Yellow River Basin	Shandong	Jinan	JN
			Weifang	WF
			Dezhou	DZ
	Haihe Basin	Hebei	Cangzhou	CZ
		Tianjin	Tianjin	TJ
Central route	Yellow River Basin	Henan	Nanyang	NY
			Zhengzhou	ZZ
			Anyang	AY
	Haihe Basin	Hebei	Handan	HD
			Xingtai	XT
			Shijiazhuang	SJZ
			Baoding	BD
		Beijing	Beijing	BJ

4.2 Evaluation standards

In the NEDEA model, a value of θ between 0 and 1 (excluding 1) implies disharmony; a value of θ equal to 1 when $s_i^- = s_r^+ = 0$ implies harmony.

In the SEDEA model, a value of θ between 0 and 1 (excluding 1) implies disharmony; a value of θ equal to or larger than 1 implies harmony (the higher the value, the higher the degree of harmony).

4.3 Data collection

Data came from the *China City Statistical Yearbook* (DUSESNBS 2008, 2009) and the urban socio-economic survey for the selected cities. These processed data (x_1 , x_2 , x_3 , y_1 , y_2 , y_3 , and y_4) are presented in Table 3 for each DMU. There is a time lag of 1 year (k = 1) between input and output due to an input-output cycle of water supply and economic development.

Table 3 Water resources and economic development data for SNWDP water conservancy area

DMU	x_1 (10^4 t)	x_2	x_3 (10^4 yuan)	y_1 (yuan per capita)	y_2 (m^3 per capita)	y_3 (%)	y_4 (%)
YZ	11 316	356	17 970	51 368	36.76	57.60	97
HA	7 502	750	17 864	17 234	27.66	84.50	97
XZ	15 699	1 321	58 635	49 247	37.75	85.90	97
JN	30 023	3 836	91 317	55 430	53.08	55.10	98
WF	9 286	349	27 165	35 726	16.92	84.77	98
DZ	5 019	421	13 571	47 705	35.90	53.32	96
CZ	4 386	408	21 264	34 323	29.01	60.00	96
TJ	68 180	4 020	109 445	51 231	25.99	78.21	97
NY	7 637	731	45 438	16 447	17.25	47.92	97
ZZ	28 073	2 510	37 423	35 499	40.27	92.37	96
AY	13 160	625	28 765	23 509	25.39	55.11	97
HD	19 609	258	43 986	29 441	27.69	51.00	94
XT	6 981	433	18 168	25 658	26.16	75.00	95
SJZ	22 764	1 666	42 334	40 312	28.12	70.63	97
BD	8 936	399	34 947	29 263	28.25	65.39	96
BJ	142 644	3 871	59 930	60 045	32.17	69.56	99

4.4 Result analysis

The results of the NEDEA model and SEDEA model are shown in Tables 4 and 5, respectively. The degrees of harmony between water resources and economic development of typical cities in China’s SNWDP water conservancy area are shown in the tables. From the results shown in Table 4, Tianjin, Jinan, Beijing, Shijiazhuang, Xuzhou, Zhengzhou, Nanyang, and Anyang cities (just half, i.e., 8 of the 16 cities) are categorized as being in relative disharmony; the others are categorized as being in relative harmony by the NEDEA model. Comparing the routes, there are greater differences among the cities along the eastern route than those along the central route. According to the SEDEA model, the order of the degree of harmony of the cities from low to high is as follows: Tianjin, Jinan, Beijing, Shijiazhuang, Xuzhou, Zhengzhou, Nanyang, Anyang, Baoding, Xingtai, Huai’an, Cangzhou, Yangzhou, Handan, Weifang, and Dezhou. However, the NEDEA model does not provide this information.

Table 4 NEDEA model results

DMU	s_1^- (10^4 t)	s_2^-	s_3^- (10^4 yuan)	s_1^+ (yuan per capita)	s_2^+ (m^3 per capita)	s_3^+ (%)	s_4^+ (%)	θ	z
YZ	0	0	0	0	0	0	0	1.00	1.00
HA	0	0	0	0	0	0	0	1.00	1.00
XZ	0	0	0	0	4.07	0	36.38	0.45	3.10
JN	0	318.78	0	13 964.79	0	28.30	48.91	0.25	6.12
WF	0	0	0	0	0	0	0	1.00	1.00
DZ	0	0	0	0	0	0	0	1.00	1.00
CZ	0	0	0	0	0	0	0	1.00	1.00
TJ	4 455.16	44.08	0	0	17.28	0	26.11	0.17	7.47
NY	0	11.94	4 881.79	18 233.53	12.06	12.71	0	0.58	1.74
ZZ	7 230.98	602.18	0	3 373.82	0	0	28.96	0.56	2.33
AY	0	0	0	23 434.46	7.40	5.75	0	0.62	1.63
HD	0	0	0	0	0	0	0	1.00	1.00
XT	0	0	0	0	0	0	0	1.00	1.00
SJZ	2 427.42	61.12	0	0	7.98	0	8.55	0.39	2.80
BD	0	0	0	0	0	0	0	1.00	1.00
BJ	35 283.59	582.40	0	0	13.57	0	24.17	0.29	4.38

Note: s_1^- represents surplus x_1; s_2^- represents surplus x_2; s_3^- represents surplus x_3; s_1^+ represents y_1 slack; s_2^+ represents y_2 slack; s_3^+ represents y_3 slack; s_4^+ represents y_4 slack; and θ is degree of harmony. z is return to scale and $z = \sum_{j=1}^{16} \lambda_j \Big/ \theta$ (if $z = 1$, return to scale of jth DMU will not change; if $z > 1$, return to scale of jth DMU will decrease; and if $z < 1$, return to scale of jth DMU will increase).

Table 5 SEDEA model results

DMU	s_1^- (10^4 t)	s_2^-	s_3^- (10^4 yuan)	s_1^+ (yuan per capita)	s_2^+ (m^3 per capita)	s_3^+ (%)	s_4^+ (%)	θ	z
YZ	5 167.33	0	0	0	3.18	4.01	14.42	1.27	0.92
HA	730.83	371.53	0	11 674.01	1.81	0	10.03	1.15	0.98
XZ	0	0	0	0	4.07	0	36.38	0.45	3.10
JN	0	318.78	0	13 964.79	0	28.30	48.91	0.25	6.12
WF	0	0	7 354.13	0	17.23	0	20.36	1.38	0.90
DZ	0	264.03	0	0	1.16	14.31	14.58	1.68	0.68
CZ	0	24.40	12 426.80	6 627.11	5.01	0	0	1.27	0.79
TJ	4 455.16	44.08	0	0	17.28	0	26.11	0.17	7.47
NY	0	11.94	4 881.79	18 233.53	12.06	12.71	0	0.58	1.74
ZZ	7 230.98	602.18	0	3 373.82	0	0	28.96	0.56	2.33
AY	0	0	0	23 434.46	7.40	5.75	0	0.62	1.63
HD	15 778.60	0	37 153.70	13 993.24	0	15.25	0	1.32	0.73
XT	355.26	0	0	9 098.90	0	0	2.69	1.12	0.90
SJZ	2 427.42	61.12	0	0	7.98	0	8.55	0.39	2.80
BD	0	0	10 821.23	11 427.61	0	0	0	0.92	1.07
BJ	35 283.59	582.40	0	0	13.57	0	24.17	0.29	4.38

The returns to scale between water resources and economic development of typical cities within China's SNWDP water conservancy area are shown in Tables 4 and 5. According to the

SEDEA model, the returns to scale of Xuzhou, Jinan, Tianjin, Nanyang, Zhengzhou, Anyang, Shijiazhuang, Baoding, and Beijing are all greater than 1, implying that they are among the cities with decreasing returns to scale, while the other typical cities are less than 1, implying that Yangzhou, Huai'an, Weifang, Dezhou, Cangzhou, Handan, and Xingtai are among the cities with increasing returns to scale. According to the NEDEA model, the returns to scale of Xuzhou, Jinan, Tianjin, Nanyang, Zhengzhou, Anyang, Shijiazhuang, and Beijing are all greater than 1, implying that they are among the cities with decreasing returns to scale, while the other typical cities are equal to 1, implying that Yangzhou, Huai'an, Weifang, Dezhou, Cangzhou, Handan, Xingtai, and Baoding are cities with constant returns to scale. Obviously, the returns to scale calculated by the SEDEA model are more accurate than those calculated by the NEDEA model.

The values of surplus variables s_1^-, s_2^-, and s_3^-, and slack variables s_1^+, s_2^+, s_3^+, and s_4^+ for water resources and economic development of typical cities within China's SNWDP water conservancy area are shown in Table 4 and Table 5. Table 4 shows that Jinan, Tianjin, Nanyang, Zhengzhou, Shijiazhuang, and Beijing have redundant inputs, while Xuzhou, Jinan, Tianjin, Nanyang, Zhengzhou, Anyang, Shijiazhuang, and Beijing have deficient outputs. Tianjin, Zhengzhou, Shijiazhuang, and Beijing have redundant water supply. Jinan, Tianjin, Nanyang, Zhengzhou, Shijiazhuang, and Beijing have redundant employees of water supply departments. Nanyang has redundant water investment. Jinan, Nanyang, Zhengzhou, and Anyang are among the cities with deficient GDP per capita. Xuzhou, Tianjin, Nanyang, Anyang, Shijiazhuang, and Beijing are among the cities with deficient water consumption per capita. Jinan, Nanyang, and Anyang are among the cities with deficient urban domestic sewage treatment rates. Xuzhou, Jinan, Tianjin, Zhengzhou, Shijiazhuang, and Beijing are among the cities with deficient employment rates. Adding water supply to Yangzhou, Huai'an, Weifang, Dezhou, Cangzhou, Handan, Xingtai, and Baoding could improve their social economic development. However, adding water supply to Xuzhou, Jinan, Tianjin, Nanyang, Zhengzhou, Anyang, Shijiazhuang, and Beijing would not improve their social economic development. Table 5 shows that all typical cities except Xuzhou and Anyang have redundant inputs, and all typical cities have deficient outputs. In detail, Yangzhou, Huai'an, Tianjin, Zhengzhou, Handan, Xingtai, Shijiazhuang, and Beijing have redundant water supplies. Huai'an, Jinan, Dezhou, Cangzhou, Tianjin, Nanyang, Zhengzhou, Shijiazhuang, and Beijing have redundant employees of water supply departments. Weifang, Cangzhou, Nanyang, Handan, and Baoding have redundant water investment. Huai'an, Jinan, Cangzhou, Nanyang, Zhengzhou, Anyang, Handan, Xingtai, and Baoding are among the cities with deficient GDP per capita. Yangzhou, Huai'an, Xuzhou, Weifang, Dezhou, Cangzhou, Tianjin, Nanyang, Anyang, Shijiazhuang, and Beijing are among the cities with deficient water consumption per capita. Yangzhou, Jinan, Dezhou, Nanyang, Anyang, and Handan are among the cities with deficient urban domestic sewage treatment rates. Yangzhou, Huai'an, Xuzhou, Jinan, Weifang, Dezhou, Tianjin, Zhengzhou, Xingtai, Shijiazhuang, and Beijing are among the cities with deficient employment rates. Actually, almost all the typical cities have either redundant inputs or deficient outputs.

Hence, the results of the SEDEA model are more precise than those of the NEDEA model. In the SEDEA model, the different characteristics of different cities are more obvious than in the NEDEA model. The SEDEA model has better evaluation results than the NEDEA model in this study area due to an important extension of super-efficiency models developed during the past decade. In comparison to the SEDEA model, the NEDEA model is only a traditional conceptual DEA model; it does not take into consideration the order of the objective function value. This indicates that the SEDEA model is superior to the NEDEA model.

5 Conclusions

We developed the SEDEA model based on the NEDEA model and the super-efficiency method, used the SEDEA model to evaluate the degree of harmony between water resources and economic development of the SNWDP water conservancy area, and compared the evaluation results with those of the NEDEA model. The main conclusions are as follows:

(1) Both the SEDEA and NEDEA models can be used to evaluate the degree of harmony between water resources and economic development in different cities in China's SNWDP water conservancy area. However, the SEDEA model additionally allows ranking of efficient DMUs.

(2) The SEDEA model describes the objective function values and returns to scale of DMUs by the super-efficiency method. Therefore, the SEDEA model can be used for relative efficiency sorting.

(3) The SEDEA model provides a reasonable description of the harmony of the study area. The SEDEA model is superior to the NEDEA model in evaluating the degree of harmony between water resources and economic development of different cities in China because it can take into consideration the order of the objective function values.

The research presented in this paper on the degree of harmony between water resources and economic development covers only a limited number of cities in China's SNWDP water conservancy area. The applicability of the SEDEA model needs further verification in more cities, and even other countries.

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